An investigation into the rehabilitation of timber structures with fibre composite materials

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ABSTRACT: Timber was the material of choice for a large number of Australian infrastructure projects during the 19th and early 20th centuries. Many of these timber structures have lasted well and remain in use today. However, some important timber structures, particularly timber road and rail bridges, are reaching a critical point in their life as codes call on them to carry loads above their capacity or their condition has deteriorated to a point where they are no longer considered safe, or a combination of both. It is often not financially viable or convenient in the short term to replace these bridges. It is proposed it may be possible for managers of civil infrastructure to be able to quickly, inexpensively and significantly improve the structural behaviour of timber bridges and extend their service life until they are able to be taken out of service and replaced. This paper investigates the use of fibre composite materials to rehabilitate timber structures such as these. In this preliminary study unserviceable timber railway sleepers are externally reinforced with carbon fibre / epoxy laminates and tested to destruction. Conclusions on the effect of the externally bonded carbon fibre laminates are drawn.

1 BACKGROUND

Australia has a significant number of timber road and rail bridges. Studies by Yttrup and Law (1991), Yttrup and Nolan (2004) and Champion et al (2002) have highlighted the magnitude of timber bridge use in Australia. In Queensland alone there is over 100km's of rail bridges consisting of 17000 spans, in New South Wales there are over 1000 timber beams bridges and 100 timber truss bridges. The significant number of timber structures is a legacy of the development that Australia underwent in the period from the early 1800's up to the early 1900's. During this time timber was the material of choice for both road and railway spanning structures due to its low cost and the local availability of high quality timber.

As these bridges age they tend to become functionally obsolete through three main mechanisms. Firstly changing usage patterns may call for wider bridges which are able to carry large volumes of traffic. Secondly, changing code requirements can call on existing bridges to carry increased loads. Thirdly, as the bridges deteriorate they become less able to meet performance requirements.

The aging of timber bridges is a significant concern to infrastructure authorities as increasing important is put on public safety and the issues of liability. To meet their responsibilities many authorities have developed sophisticated tools based on algorithms that consider structural, traffic network, social and economic factors, to help identify critical bridges and predict remaining life. The tools are often able to rank the bridges in order of those most in need of attention.

In some cases it is possible that lack of time, resources or funds restricts the ability of infrastructure managers to address timber bridge problems in a permanent manner. In some cases load, speed, or access restrictions are applied to bridges limiting their use until the issue can be addressed either permanently or temporarily. Unlike most existing concrete bridges, timber bridges would ideally be replaced (usually by concrete) when they become critical rather than repaired. However repair of timber bridges remains a favourable option in the absence of funds needed to replace the bridge with one of concrete.

To this end many methods have been developed to rehabilitate timber bridges. Current methods include deck replacement, member substitution or splicing and banding of members. These methods are usually carried out by unskilled labour. In some cases replacement timber members are difficult to find and alternative materials such as steel and, from time to time, fibre composites are used.

Anecdotal evidence suggests that some road authorities have attempted to use externally bonded fibre composite materials to improve timber bridge performance. However, advice received by the author indicates that the method has not received widespread acceptance due to early failure of the repair in some cases. Issues such as use of unskilled labour and poor supervision appear to have led to poor installation or inappropriate use ultimately causing early failure of the repair. Nevertheless in some cases the method apparently has worked well.

Despite the apparent inability of externally bonded fibre composites to provide a suitable repair solution for all timber road bridges it was used in, the pioneering work done to investigate its use should be considered invaluable. The practical nature of bridge repair necessitates a repair method which is based on a practical approach. If the use of externally fibre composite materials to rehabilitate timber bridges has failed in some cases in the past then these should be the basis for a more thorough investigation. It should not be the aim to expect that externally bonded fibre composites would be the only method of repair for timber bridges, but in some cases where traditional repair methods aren't possible, the option to use this method might provide a suitable alternative.

This situation is not all that different from the development of the use of fibre composite materials in the civil engineering industry in general.

The use of fibre composite materials in civil engineering type applications is becoming more popular. Over the last two decades significant advances in the use of fibre composites as rehabilitation materials for reinforced and stressed concrete have been made.

There are a number of reasons why fibre composite materials have found favour as rehabilitation and retrofitting materials for concrete structures. These include availability of standard externally applied fibre composite reinforcement systems, greater knowledge of the use of fibre composites by engineers and designers, greater access to fibre composites based rehabilitation and repair service providers, savings in cost in some applications from easier installation, improved understanding of material characteristics as well as installation and geometric versatility of the material.

However, despite the use of fibre composite materials in bona-fide rehabilitation projects, a number of issues remain unresolved. These include inability to accurately cost non-standard installations, lack of information for specification, lack of specific material information and incomplete understanding of long-term behaviour.

Fibre composite materials have been used to rehabilitate timber concrete and steel structures. However, the use of fibre composite materials to rehabilitate steel structures is much less common than for concrete or timber and is often limited to solving corrosion or wear problems. One of the reasons that fibre composite materials are not widely used to strengthen steel structures is their relatively low elastic modulus and the need to undergo reasonably large strains to develop their characteristic strength.

The use of fibre composite materials to rehabilitate concrete is far greater than that of timber or steel structures. This is likely to be due to two main reasons; firstly the much greater number of key concrete infrastructure and secondly the tendency for asset managers to replace timber infrastructure rather than rehabilitate.

But in some cases timber structures are of historical value. It is often these historical timber structures which benefit from characteristics offered by composite materials through provision of a simple, effective, unobtrusive and inexpensive rehabilitation solution.

The success of fibre composites to rehabilitate timber structures relies heavily on the condition of the timber structure, the ability of the fibre composite materials to bond with the surface of the member to be rehabilitated and the ability to access areas of the structure which require attention.

One issue which prevents fibre composite materials from being useful to rehabilitate timber structures is that timber structures can remain safely in service and carry significant load despite suffering significant physical degradation. This was identified by Law et al (1991). In these cases it may not be possible to rehabilitate the structure. In other cases it may be possible to remove the outer layer of timber and apply a high build primer to provide an appropriate surface for application of the fibre composites.

Successful external bonding of fibre composite materials to timber members can potentially experience considerable strength and stiffness improvements (Triantafillou and Deskovic, 1992; Galloway, 1996). One of the benefits of composite materials such as carbon and Kevlar is that their gross section modulus is generally higher than that of timber (particularly carbon fibre composites) and materials such as timber are tolerant of larger strains needed to develop the characteristic high strength of fire composites.

In some cases it will be possible to change the location of neutral axis in timber bending members and hence provide a greater area of timber to take the compression stresses. This was apparent in work undertaken by Davalos et al (1999) who investigated the use of glass fibre reinforced epoxy laminates externally bonded to timber railroad ties.

2 AIMS

The main aims of this study were to initiate research into this area at QUT, to demonstrate the potential increase in strength and stiffness that could be gained with externally bonded fibre composites and to investigate practical issues associated with rehabilitating aged timber structures.

In order to demonstrate the ability of externally bonded fibre composite materials to improve strength and stiffness of existing timber structures, this pilot study focused on the application of fibre composite materials to simple timber beams. Railway ties were chosen for their geometry, availability and the type of material and degradation that they had undergone.

It is hoped that the fundamental information gained from this study could be extended to provide a useful base from which further study into larger structural members, such as bridge members, could be undertaken.

3 SPECIMENS AND MATERIALS

Timber railway sleepers are discarded in different states of well being. These range from severely deteriorated with significant signs of physical degradation, to those which have been incidentally removed due to the economics of replacing track sections, rather than individual ties. Figure 1 shows an example of the type of variation in physical condition that could be observed in groups of discarded timber sleepers. These could be seen as representative of the type of tie condition that a rehabilitation system would have to be able deal with.

Figure 1 – Unserviceable timber railway sleepers

A number of timber sleepers were visually inspected at the storage site and chosen for their general representation of in situ sleepers and suitability to the test. For reasons of cost the number of sleepers was limited to three, with two finally chosen for testing. Research has found that despite evidence of significant physical degradation, timber railway sleepers can still function properly in some cases (Simpson, 1999). Therefore characteristics sought after included a length of between 2.4m and 3.6m, reasonable physical condition – in particular the top face.

These were judged to be representative of the physical condition of a sleeper that would be available in service in the worst possible condition that could still accept fibre composite skins with only basic preparation. One important characteristic needed to be possessed by the specimens was that their lower face should be in reasonably good physical condition to permit laminating of the external fibres. Figure 2 shows the bottom surface of one of the test specimens that was in reasonable good condition.

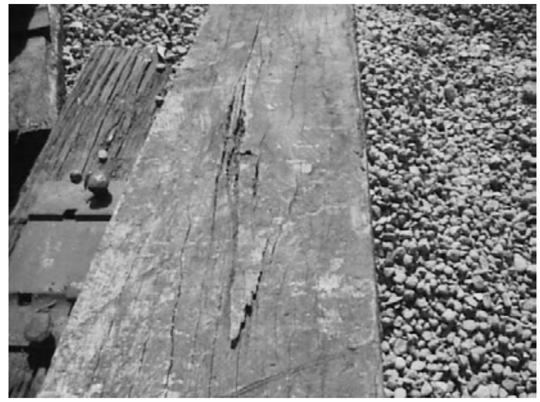

Figure 2. Typical base of sleeper specimen

Positive identification of the timber specimens was not possible at the time of writing however visual inspection suggested that the sleepers were made from locally available Australia hardwood known as ironbark. Two specimens were chosen for testing and are referred to in this paper as “Specimen 1” and “Specimen 2”. Moisture content (MC) was measured and showed Specimen 1 possessed a MC of 12% and Specimen 2 possessed a MC of 14% at the time of laminating.

The sleepers were tested in three-point bending to determine their flexural elastic modulus. Figure 3 shows the basic test configuration.

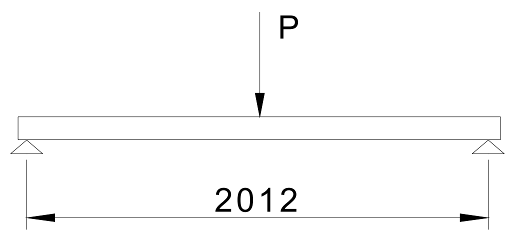

Figure 3. Three-point bending sleeper test

Specimens were loaded to 50% of their estimated flexural failure strain ($\varepsilon_{ult.f} \approx 1\%$). In addition to this clear specimens were cut from sleepers of the same material and tested to destruction to provide additional flexural modulus data as well as values of failure strain and failure stress. These tests were carried out in accordance with ASTM standard “D143 - Standard Methods of Testing Small Clear Specimens of Timber” (ASTM, 1994). Table 1 provides the mechanical properties derived from these tests.

Table 1 Timber mechanical properties

$\varepsilon_{ult.f}$ (%)	$\sigma_{ult.f}$ (MPa)	E_f (MPa)
0.995	103.85	10575

The bottom face of the sleeper needed to be dressed to accept the fibre composite laminates. This was accomplished by removal of the outer layer of wood on the bottom surface of the sleeper by slicing and dressing two 75mm wide strips of outer material to a depth of 15mm on the bottom surface. Figure 4 shows a typical prepared specimen.

Figure 4. Typical prepared sleeper specimen

Carbon fibre / epoxy laminates were proposed for this series of tests due to the carbon's failure strain and elastic modulus and epoxy resin's bonding ability. 300gsm unidirectional fibres were sliced into 75mm wide strips and hand-laminated onto the dressed bottom surface of the sleeper. The laminated strips were post-cured at 80°C for 8hrs. Figure 5 shows the sleepers during post-curing.

Figure 5. Post-curing carbon / epoxy sleeper laminates

Additional carbon / epoxy laminates were made and tested in accordance with ISO527 - Plastics - Determination of tensile properties - Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites (ISO, 1997). The results from the tests are contained in Table 2.

Table 2 Carbon / epoxy laminate mechanical properties

$\varepsilon_{ult.f}$ (%)	$\sigma_{ult.t}$ (MPa)	E_t (MPa)
1.65	1488	90018

4 ANALYSIS

Hand calculations using fundamental engineering principles and the material properties provided in Tables 1 and 2 were used to predict failure load and deflection of the test specimens. Calculations were based on the following assumptions:

1. The carbon laminates would remain bonded to the sleeper until tensile rupture of the bottom face of the sleeper.
2. Failure of the outer tensile timber fibres will cause instantaneous failure of the bond between the carbon fibre laminate and the sleeper, resulting in complete loss of load carrying capacity.

The carbon / timber cross section was transformed into an equivalent timber cross section using the properties contained in Tables 1 and 2. Introduction of the carbon laminates lowered the neutral axis to a position 65.866mm below the sleeper's top surface and resulted in a moment of inertia of I_{xx} = 43.8147E6mm^4.

These values were used to derive the expected ram load at failure, thus:

$$\varepsilon = \frac{My}{EI_{XX}} \tag{1}$$

$$0.00995 = \frac{M \times 39.134}{10575 \times 43.8147E6}$$

$$M = 117.806kNm$$

The ram load at failure was therefore expected to be 234.207kN with a midspan deflection of 85.769mm. This is more than double the estimated load capacity of the unreinforced timber sleeper, which can be derived using the same formula and values, except that I_{XX} = 33.12E6mm^4, giving a capacity of 115.47kN.

5 TESTING AND RESULTS

The carbon / timber sleepers were tested to destruction in three-point bending in a universal testing machine. Figure 6 shows the test configuration. The test geometry was given in Figure 3.

Figure 6. Typical test configuration

The specimens were subjected to an increasing monotonic load at a rate of 4mm/minute to destruction. Load, midspan bottom deflection and midspan tensile strain were measured. Figure 7 provides graphical results of the testing and Table 3 provides a summary of results.

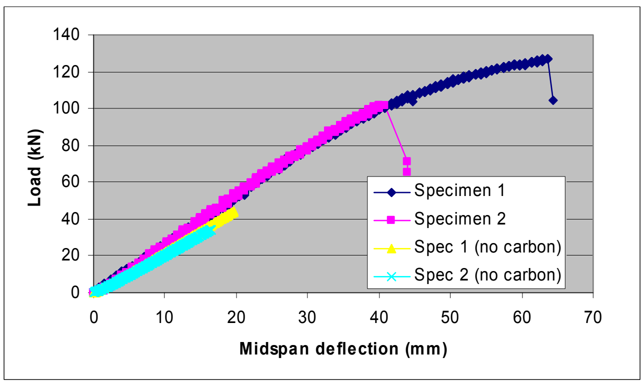

Figure 7. Load versus midspan deflection of carbon / timber sleepers and plain timber sleepers

Table 3 Carbon / timber sleeper summary of results

Specimen	P_{ult} (kN)	δ_{max} (mm)	ε_{ult} (%)
1	127.15	63.77	0.77
2	101.81	40.88	0.48

In both cases the carbon / timber sleepers failed to achieve the expected levels of load carrying and failure strain. This may be explained by considering the mode of failure.

Failure in both cases was instantaneous and catastrophic with no evidence of post failure strength. There was some audible warning of overload just prior to failure. Failure in both cases consisted of delaminating of the carbon / epoxy laminate, with the laminate and the surface of the sleeper remaining in good condition.

Close visual inspection revealed little penetration into the timber by the epoxy resin. It also appeared that the surface preparation undertaken on the timber resulted in a very smooth surface which had prevented keying of the resin into the wood. Figure 8 shows the failed specimen and the smooth surface on both the carbon laminate and the timber sleeper indicating poor bonding.

Figure 8. Failed specimen showing smooth surface of timber sleeper (bottom) and smooth surface of carbon laminate (top)

The poor bonding of carbon strips to the timber may have also contributed to the slightly non-linear nature of the graph as a result of poor shear transfer between the timber and the laminates.

The graph of Figure 7 also shows a marginal increase in gross member stiffness due to the addition of the carbon strips. This is not surprising considering the movement of the neutral axis due to addition of the carbon fibre strips. The neutral axis moved downwards approximately 13mm, resulting in an additional 2990mm^2 of cross sectional timber area carrying compressive load. However, the curves tend to indicate that at higher load the carbon reinforced timber sleepers could have shown a more significant increase in stiffness.

6 CONCLUSIONS

Hand calculations showed that potential exists to significantly increase the load carrying capacity of the timber. However, this can be limited by the development of peel stresses and horizontal shear stresses and premature delamination of the fibre composite laminate.

Failure of the test specimens occurred due to delamination of the carbon fibre laminates. It is suggested that surface preparation of the timber sleepers may have contributed to this. It is also thought that the low MC and high age of the timber may have also contributed to poor penetration of the resin through tightly packed grain.

Further investigation into the ability of the carbon fibre strips to bond to timber is required.

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